The Discharge of Electricity through Vacuum Tubes.[1]

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DISCHARGE tubes with cold electrodes and low gas pressure present a great variety of complex phenomena which, at the time of their discovery, were most difficult to explain. Many of these old difficulties remain, but some have been cleared away or are in process of being cleared away in the light of recent work. In any event, within the last few years sufficient new points of view have been put forward and fresh phenomena discovered to warrant recollection of the past and special notice of the present.

With the gas pressure in the neighbourhood of 1 mm. of mercury and the discharge passing along a straight cylindrical glass tube furnished with plane electrodes, the appearance shown diagrammatically in Fig. 1 is presented. For convenience we may consider the discharge under three headings.

1. *The cathode region*, comprising the softly luminous cathode glow, the Crookes' dark space and the negative glow.

2. *The anode region*, consisting of a very thin layer of light over the anode surface.

3. *The central region of the tube including the positive column* continuously glowing, sometimes striated, separated from the cathode region by the Faraday dark space and extending right up to the anode.

These are the usual, easily recognisable divisions of the discharge with cold electrodes and a steady applied potential of a few hundred volts.

Speaking generally, the current passing through the tube will be carried almost entirely by electrons and positive ions, negative ions being comparatively unimportant. Owing to the difference in nature of these two types of carrier, however, and their interdependence, important space charge effects within the tube and area charge effects on the walls are set up, which play an important part in determining the electric forces and thus the nature of the discharge. We shall outline these and other matters in what follows.

1. *The Region of the Cathode.*

The cathode is the seat of origin of the very speedy electrons—the cathode rays—which often possess a velocity little short of that given by the usual relation

$$eV = \tfrac{1}{2}mv^2,$$

where V is the potential difference between the cathode and the edge of the dark space—the so-called cathode fall.

The dark space edge is inexplicably sharply defined and is imagined to represent the region where there is not only ionisation by the cathode rays but also recombination resulting in light emission. This is probably bound up in the fact that the electric field in the dark space has a high value whereas in the glow the field is very much smaller.

This matter of the value of the electric field is of great importance in the theory of the discharge. Measurements, whether made by the much criticised probe method or by Aston's transverse cathode ray method, show that the axial field X increases linearly with distance from the dark space boundary to the cathode. Brose, by a most ingenious method based on observations on the Stark effect in the weak light emitted from the dark space region, has recently shown that *very close to* the cathode there is a sharp drop in the electric field. This is shown in an exaggerated manner in Fig. 1. This state of affairs in the dark space is regarded as due to the space charge effects.

It was shown long ago by Schuster, Wehnelt and others by placing obstacles in the dark space that there was a "shadow" thrown both ways, so to speak, the supply of electrons from the cathode and the positive rays approaching thereto being simultaneously cut off. It was inferred that the main supply of electrons from the cathode arose somehow from the arrival there of positive ions originating in the edge of the negative glow. We conclude therefore that, since the speed of the ions is so much smaller than the electrons, there will be, on the whole, a concentration of positive electricity in the dark space. We should thus be able to obtain an expression for the variation of X by applying Poisson's law,

$$\frac{dV}{dx} = -4\pi\rho,$$

in much the same manner as in Langmuir's well-known application to the thermionic valve.

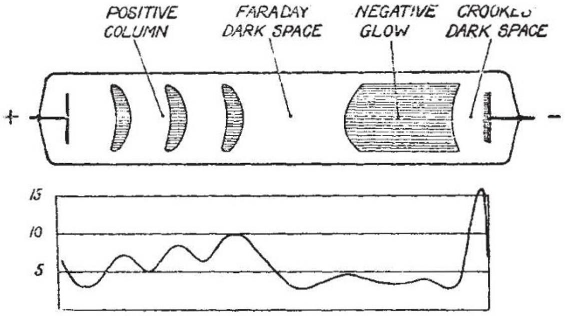

FIG. 1.—Diagrammatic representation of the regions in an exhausted tube, with, below, a curve showing the changes in the electric field in passing along the tube.

The form of the expression obtained, however, will clearly depend on the assumption made as to the distribution of positive electricity in the dark space. Assuming an impartial distribution of the positives in the dark space—an assumption incidentally not in accord with the generally accepted view of ion production outlined above—Sir J. J. Thomson deduces an expression for the electric field in accordance with the experimental results of Aston.

Very close to the cathode, on the other hand, the expression would scarcely be expected to hold, since here, production of electrons by ion bombardment is taking place, resulting in a negative space charge and a consequent lowering of the field. This brings Brose's experimental result into line.

It is interesting to note in passing that it is not an entirely straightforward matter to explain how electrons are produced at the surface of the cathode by positive ion impact. For although the whole energy of the approaching ion is adequate, this energy can only be handed over in part—and a very small part, a consideration which, when taken into account quanti-

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[1] Substance of three Tyndall Lectures delivered at the Royal Institution on May 19, 26, and June 2.

tatively, leads to the result that insufficient energy to effect ionisation is actually available.

The most likely explanation appears to be that the ion on reaching the cathode captures an electron, radiates at the appropriate frequency, and it is this radiation which ejects from the cathode low speed electrons destined to form the cathode rays. We should expect on this view that the heating effect at the cathode would represent nearly the whole energy of the incident positive rays, an expectation in accordance with the facts.

2. *The Anode Region.*

Just as there is a jump of potential near the cathode in passing across the dark space, so there is an anode fall of potential.

The anode fall, however, appears to be capable of easy explanation. It is not at all dependent on the nature of the electrodes but only on the gas and on the current flowing. Moreover, as the current is diminished the anode fall rises to a constant value which approximates very closely to the ionisation potential of the gas.

We conclude, therefore, that the cloud of negative electrons near the anode produces this anode fall, and that at small currents its nature is such that single impact ionisation occurs at the anode surface, this ionisation taking place perhaps in a film of gas on the electrode. At high current densities the anode fall diminishes, probably because cumulative ionisation then takes place.

3. *The Central Region of the Tube.*

The positive column which occupies the central portion of the tube is in many respects the most puzzling part of the discharge. Separated from the negative glow by the Faraday dark space and extending right up to the anode, its character is usually independent of the length or shape of the tube; it is sometimes a uniform column of light, sometimes—particularly when the gas is impure—striated. The conductivity of this region is high and the electric force small.

It has usually been supposed that for the continuous positive column there is a copious supply of electrons moving with ionising speed under an electric field partly determined by the space charges and partly by the charges on the wall of the tube. It is clear that the electrodes themselves cannot contribute, directly, at all to this field.

The emitted light has been supposed to be due to ionisation and subsequent recombination, which latter process is encouraged by the small electric field—in contradistinction to the state of affairs in, for example, the Crookes' dark space. The striations have been supposed to be a repetition of the state of affairs near the cathode, the non-luminous spaces between the striations being the equivalent of the Faraday dark space.

It is an interesting fact, however, that even with the perfectly steady potential from a battery of storage cells applied to the tube, it is very usual to find that the current itself is regularly intermittent, a phenomenon which has been known for many years but has never been explained.

I pointed out recently (Proc. Camb. Phil. Soc., 1924) that this effect is particularly marked in the case of the discharge through argon, and that if the tube be made of quartz and a current of several amperes passed to produce a brilliant luminosity, then most beautiful effects are observed if the tube be viewed in a mirror rotating rapidly about an axis parallel to that of the tube. Fig. 2 is an untouched reproduction taken from an instantaneous photograph obtained in this way. It will be seen that the appearance presented is that of a number of straight, parallel equidistant lines inclined at an easily measurable angle with the horizontal. The heavy horizontal line is a superimposed photograph of the glowing tube viewed in the mirror at rest. The narrow vertical line on the extreme right of the equally spaced markings is a photograph, in the same spinning mirror, of a little mercury vapour lamp fed with alternating current of about 40,000 frequency from an oscillating thermionic valve.

Interpreted broadly, this photograph shows that, so far as the luminous character of the discharge is concerned, flashes of uniform speed follow each other at equal intervals of time down the tube moving from anode to cathode. Their velocity and frequency past any point in the tube may be calculated from their inclination and distance apart.

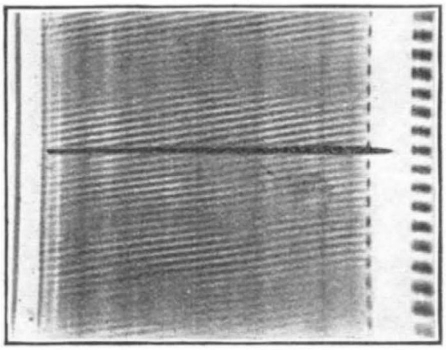

FIG. 2.

When it is remembered that these discontinuities in the discharge occur with a steady applied potential and are practically independent of any capacity, inductance or resistance, included in the circuit, it will be seen that the phenomenon is well worth remark and further investigation. It is intended at the moment to give only a very general account and explanation so far as the available experimental evidence will allow.

In the first place—as might be expected on almost any reasonable theory—the velocity of the flashes increases as the gas pressure is reduced, being nearly proportional to $1/p$. For a given strength of electric field this is what is to be expected if the moving flash consists of or is associated with moving electrons or ions. The speed is, however, also determined in part by the strength—or rather average strength—of the current, increasing somewhat with greater currents. At the same time the frequency—indicated by the distance apart of the flashes—also increases as the velocity increases, in many cases, in nearly the same proportion.

A highly important fact which came out quite early in the experiments is that the emitted light, when examined with a spectroscope of high resolving power (a spectroscope fitted with a Fabry and Perot étalon), shows no signs of the Doppler effect. That is, when the spectrum is viewed at right angles to and along the axis of the tube, there is no detectable change of wavelength in any of the lines suitable for examination. Had the sources of emission been moving with the speed of the flashes an effect should certainly be observable.

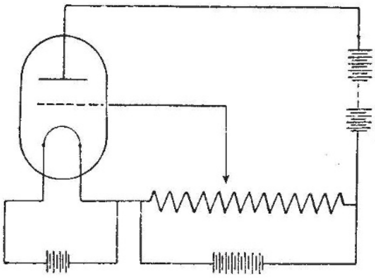

FIG. 3.

I think that an explanation (although another is possible) of this flash phenomenon may be based on a rather similar effect I chronicled in 1919 in the late *Radio Review*. If an ordinary thermionic valve containing a trace of mercury be linked to a non-inductive circuit as in Fig. 3, then if the potential (V) applied to the grid be varied between certain limits, the current in the valve circuit oscillates at a frequency (n) such that n^2/V is constant. It was shown that the effect can be satisfactorily explained on the reasonable supposition that there is some particularly active electron-emitting point on the valve filament which, when bombarded by positively charged mercury ions, emits still more vigorously (whether by space charge neutralisation or by local heating is immaterial to the general idea); the result is that there are set up regular sequences of electrons flowing to the grid in a negligibly small time and positive ions produced in the region of the grid and falling back to the filament. The time taken by these positives in travelling from grid to filament determines the oscillation frequency. In the note referred to, it was shown that a quantitative explanation along these lines is possible.

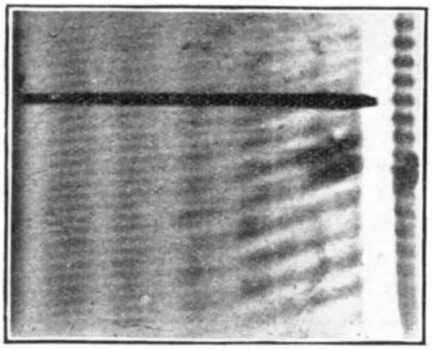

FIG. 4.

It would seem that a similar explanation might be made in the case of the flashes in the long discharge tube. The anode, on this view, would be the seat or origin of the flashes. We suppose a cloud of electrons round the anode; only those starting from a certain minimum distance will ionise at the anode surface. As soon as this occurs a sheet of positive ions will move away from the anode at a speed determined by the electric field, but the presence of this positive sheet constitutes a space charge which will so reduce the field in its train as to prevent further ion production; it therefore moves away as an isolated sheet of ionisation—to be followed in due course by a similar one produced in a similar manner. Why is not the Doppler effect observed? The suggestion is that the visible light emitted is not due to these moving ions but is a state of affairs produced by them. We must imagine that invisible radiation is given out which excites (possibly without ionising) the relatively immobile atoms of gas past which the radiating ions move.

There is some evidence, however, which it is not proposed to discuss here, in favour of a modified view of the ordinary discharge recently propounded by Günther Schulze. This investigator suggests that where a stream of electrons moving with high speed encounter and ionise (or excite) gaseous atoms, the spent electrons may produce a space charge. I merely wish to mention here that it is possible to give an alternative explanation along these lines but at the same time to point out that it is by no means impossible that both mechanisms operate, according to the conditions obtaining within the tube.

When the gas in the tube is pure it is usual to observe the appearance shown in Fig. 2, but after the discharge has passed for some time, there appear in the rotating mirror two sets of flashes; those at the anode end being much steeper, *i.e.* more slowly moving, than those at the cathode end. A reproduction of a photograph of this kind is shown in Fig. 4.

I believe this to be due to the presence of a little hydrogen. If the spectrum of the light emitted be examined, it is found that near the anode the spectrum of hydrogen is strongly developed, while near the cathode it is absent or very weak. Now the slopes of the two sets of flashes are such as to suggest that the slow ones are due to argon ions and the fast ones to

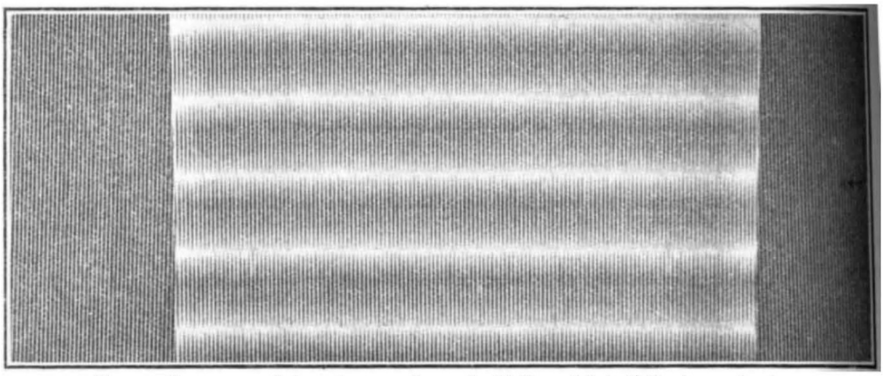

FIG. 5.—Two coarse-ruled gratings superimposed with lines slightly inclined to each other.

hydrogen ions. This at once suggests a reason for the spectrum distribution just mentioned, for where the fast flashes occupy the tube, all or most available hydrogen will be taken up in the form of non-luminous ions and the radiation they emit will only have argon atoms on which to work. The hydrogen spectrum will therefore be weak or invisible.

So far we have been walking on fairly solid ground, but it is interesting to observe in conclusion that the definite experimental proof of the existence of these two sets of flashes through an impure gas may be made the basis of a somewhat speculative suggestion as to the origin of the familiar vacuum tube striations. We have only to suppose that in the impure gas there are two sets of flashes moving with different speeds and in simultaneous existence along the tube and we get at once that if the velocities are related in a certain manner, continuous steady striations occur where the two sets cross. An example of this combination effect is shown in Fig. 5, which is a photograph of two coarse-ruled gratings with their lines slightly inclined to each other. The edges of this photograph clearly show the lines of the two gratings separately and the central part where they are superimposed. The horizontal equidistant bands in this superimposed area are parallel to the shorter diagonals of the parallelograms produced by the intersections of the two sets of mutually inclined lines, and, according to our speculation, would represent the striations as seen in the rotating mirror. Further experiments, however, must be performed before anything more definite can be put forward.

A Cotton Research Station for the British Empire.[1]

It has long been a weak point in the scientific investigation of the agriculture of the British tropical dominions that we have had no stations where problems that are fundamental and underlying, affecting all tropical countries alike, could be attended to. Local departments of agriculture are necessarily and rightly occupied with local questions, and authorities might look askance at such a department if it were to devote itself, for example, to the fundamental problem of the connexion between lint characters in cotton and spinning qualities.

This defect in our organisation is now to be removed, so far as cotton is concerned, a forward step of great importance having been taken by the Empire Cotton Growing Corporation, which, with the express aim in view of the solution of problems of this nature, has decided to open in Trinidad a cotton research station, near the Imperial College of Tropical Agriculture. The station is to be provided with a first-rate staff, and well endowed with funds, so that great results may be expected from this far-seeing enterprise.

"It is intended to investigate there the cotton plant in all phases of its growth and under rigorously controlled conditions, so that it may be possible to ascertain and to estimate the importance of the several factors which contribute to the final result." In other words, it is in no sense intended as a local station for the investigation of problems which are of local origin and can only be solved under corresponding local conditions, nor is it intended as a place for the breeding of pure-line seed upon a large scale. Such seed, with various special characteristics, will indeed be produced, but when it is introduced into other places, the effects of acclimatisation (at present not understood) will come in, and it is for each individual country to produce from the seed the cotton that is best adapted to its local conditions. Much labour in breeding will thus be saved to the local workers, for they will start from seed of known genetic qualities. The new station will not relieve the local agricultural departments from the necessity of scientific work upon their local problems, but will provide them with better fundamental knowledge upon which to base their investigations.

Since it was decided to establish the station, a strong committee has been at work considering the claims of various places in the warmer parts of the British Empire, and at last, by a process of gradual elimination, decided that Trinidad was the most promising. Prof. J. B. Farmer and Mr. L. G. Killby (secretary of the Corporation) were then sent out to report in more detail, and as a result Trinidad has been finally selected.

In his preface Dr. W. L. Balls directs attention to the fact that it was the late Mr. J. W. McConnell (first chairman of the Council of the Corporation) who was chiefly responsible for the achievement of this result—a result which even ten years ago would have been considered Utopian.

Trinidad is suited, in the neighbourhood of Port-of-Spain, to the cultivation of cottons of many different kinds, but has not proved commercially successful in their growth, so that the cottons upon the station will not be liable to hybridisation with others growing near by—an important advantage. It is easily accessible from England, and from the other countries of the American continent where cotton is cultivated on the large scale. It has a good and healthy climate, and the site chosen is near to the capital town, while it is also near to the Imperial College of Tropical Agriculture, thus placing its staff in close contact with the workers in the latter, and with the facilities there provided. This is another advantage of great importance to both parties, especially as a good many of the future employés of the Corporation are trained at the College, and will thus have the station near at hand, and be in a position to get upon friendly terms with the staff, from whom they will be able to get useful hints in their work.

The site is an area of sixty acres, about one-third of which will be planted in cotton every year, with cane as a rotation. It is proposed that work be begun by the appointment of a geneticist and a plant physiologist, each with a competent understudy and the needful assistance, including frequent study-leave and travel. The management and general direction it is proposed to entrust to a local advisory committee of two—Dr. H. Martin Leake, Principal of the Imperial College, who has done much research work upon cotton, and Mr. W. Nowell, Assistant Director of Agriculture in Trinidad, well known for his work in mycology, etc. These gentlemen will act in their private and not in their official capacity. It is also hoped to arrange for exchanges of staff with the Shirley Institute of the British Cotton Industry Research Association.

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[1] Summary of a Report to the Empire Cotton Growing Corporation, by Prof. J. B. Farmer and Mr. L. G. Killby, with a foreword by Dr. W. L. Balls (London, 1925).